Potential effects to ground-water systems resulting from subsurface injection of coalbed methane production water

Report to the Montana Department of Environmental Quality and the Board of Environmental Review

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Purpose

The purpose of this report is to present a brief discussion of the potential effects of injecting coalbed methane (CBM) production water on ground-water flow and chemistry within various hydrologic units of the Powder River Basin (PRB) that have been identified in previous and ongoing studies. For the sake of brevity, the discussion addresses general concepts and is not a site-specific assessment. The highly variable hydrologic and geochemical conditions within the PRB do not support blanket statements that cover all sites and issues. Moreover, other areas of Montana, if developed for CBM, may have very different water resource issues both in terms of the volume and quality of production water and the effects of injection on local aquifers.

Injecting CBM-production water into aquifers is one water-management option used by production companies and increased use is being considered. Under the proposed rule change, injection would be mandated (with exceptions where it can be proven to be technically unfeasible) by the Board of Environmental Review.

Overview

Coalbed methane production water, for the purpose of this report, describes the water pumped from coal seams to release methane. Management of production water is a major concern for CBM producers and landowners alike. Pumping and disposing of the water is an expense for the CBM companies, but coal-aquifer water is a resource for the agricultural community in southeastern Montana, providing domestic and stock-water supplies. Due to the high sodium content, however, discharge of the water on the land surface has the potential to damage soils and significant amounts discharged into streams can change both regimen and chemistry. Reaching a balance between the needs of the CBM companies and the affected community is critical for continued development of the gas resource in Montana.

Production of CBM began in Montana in 1999. Total CBM-water production during 2004, in Montana, was 673 million gallons (2,065 acre-feet) over a CBM-producing area of about 19 square miles. After 5 years of CBM production in Montana the average water discharge per well was 3.2 gallons per minute (gpm). This water-production rate is about 50% of the rate that was predicted after 5 years of production (U. S. Bureau of Land Management, 2003), indicating that water-management plans may address smaller quantities than originally expected.

The purpose of production-water management is to remove the water from the coal beds and dispose of that water in a manner that minimizes risks yet allows CBM development to be economical. Preferable options address the need to conserve the water resource, and to maximize positive effects while minimizing negative effects to soils and streams. Currently, the choices for discharge of the production water include direct discharge to streams, treatment such as sodium removal followed by direct discharge to streams or other beneficial uses, infiltration to shallow aquifers through ponds, evaporation, irrigation, stock water, industrial use of the water, and injection. The quantity and quality of water produced is highly variable and local factors (such as: soil types, industrial demand for water, and potential injection target zones) also vary across the basin. Due to the variable nature of the challenge, a "one size fits all" approach is likely to miss opportunities to minimize impacts economically.

In Montana, CBM is currently only being produced in the PRB, an area that is unique in that the coal beds are aquifers that produce water for stock wells and springs. Some of the extensive coal reserves that underlie other areas of the state may become targets for CBM production in the future. In those areas, the local conditions and water resources may be much different than in the PRB and production water may be managed in a much different manner.

Injection description

In selecting an injection zone or horizon, operators use several evaluation criteria. The zone must be separated from CBM production to avoid recycling water into the production area and increasing pumping costs and volumes. Injection zones must be capable of receiving sufficient water to offset the cost of construction of the injection well and associated infrastructure. The amount of water that can be injected will depend on the available storage capacity of the aquifer (confined, unconfined or a combination of both) and the horizontal and vertical hydraulic conductivities that allow the water to move away from the injection well.

In order to avoid surface release of injected water, the target horizon should be below land surface within the area of influence of the injection well. Therefore, target zones would be at an altitude that is below that of adjacent stream valleys and would not crop out in nearby areas. The chemistry of water in receiving zones should be compatible with that of CBM-production water to avoid reactions that can encrust well screens, dissolve minerals in the aquifer material that can change water quality, or precipitate minerals which can also change water quality and plug aquifer pore spaces. Also, the injected water should not diminish the usability of the formation water.

Target horizons are identified using existing geologic data such as geophysical well logs. After an injection well is constructed and initially tested, the infrastructure (pipelines and pumps) to bring discharge water from several CBM wells is constructed. Injected water is forced into the receiving formation under pressure. The amount of pressure that can be used in an injection well is based on the depth of the well and is specified in the injection permit.

Wells are defined as structures that are deeper than they are wide. For this reason, infiltration ponds cannot be classified as injection wells, however they do perform the same functions and are briefly mentioned below.

Existing geology and ground-water systems

Geologic formations that are exposed at land surface in the PRB are alluvium along streams, clinker on ridge tops, the Wasatch Formation, and the underlying Fort Union Formation. The Wasatch Formation is generally limited to the higher ridges in the southern portion of the PRB in Montana, so is not a viable target for injection. The Fort Union Formation is the predominant geologic unit at land surface in the PRB in Montana.

The Fort Union Formation is subdivided into three members: the uppermost Tongue River Member, the middle Lebo Shale Member and the basal Tullock Member. The Tongue River Member consists of interbedded shale, sandstone, siltstone and coal, and has a total thickness that varies from about 750 feet near the edges of the basin to 3,000 feet near the basin axis. Drilling logs from MBMG monitoring wells installed during the past 3 years indicate that less than 40 percent of the Tongue River Member (of the 8,649 feet that was penetrated at 16 sites) is made up of potential aquifer material (25 percent sandstone and 14 percent coal). The remainder is siltstone and shale having low hydraulic conductivity values that cannot transmit significant quantities of water. The sandstone has a wide range of hydraulic conductivity values due to grain size, sorting, and cement that fills the pore spaces. A previous study of a limited area of the PRB in Montana found that only 9 percent of the area was underlain by thick channel sandstones within the Tongue River Member (David Lopez, personal communication). Within the areas underlain by channel sandstones, the total thickness of the Tongue River Member varied from 800 feet to 2,500 feet and the total thickness of sandstones with injection potential was between 100 and 300 feet, distributed over multiple sandstone units.

Recharge to Tongue River Member aquifers occurs both as regional recharge along the margins of the PRB and locally along clinker-capped ridges. The proportion of each recharge source is not known. Ground water flows generally northward, with some topographical control toward valleys, and most of it discharges above the Lebo Shale to springs and streams. A relatively minor amount of the ground water is intercepted by water wells. That portion discharged to streams is lost as evapotranspiration or leaves the area as stream flow. The Tongue River receives approximately 23 cubic feet per second (cfs) of ground-water discharge from the Tongue River Member between the Tongue River Dam and the Brandenburg bridge (Woods, 1981; Vuke and others, 2001a; Vuke and others, 2001b).

Variation in water quality in Tongue River Member aquifers along flow paths has been documented by Van Voast and Reiten (1988). Generally, water quality in recharge areas is dominated by ions of calcium (Ca), magnesium (Mg) and bicarbonate (HCO_3). Sulfate (SO_4) concentration increases with depth as does the total dissolved solids (TDS) load. With contact with shale, the sodium (Na) concentration increases and Ca and Mg concentrations decrease. In deeper systems, SO_4 is removed by bacteria and the water quality is dominated by ions of Na and HCO_3. Coalbed methane production water is from the deeper Na- and HCO_3-dominated systems and is expected to have a moderate TDS concentration (approximately 570 milligrams per liter (mg/L) to 2,000 mg/L) (Wheaton and others, 2005).

The Ground-Water Information Center (GWIC) (http://mbmggwic.mtech.edu/), operated by the Montana Bureau of Mines and Geology, identifies 2,779 stock and domestic wells that are completed in the Tongue River Member in the PRB (Figure 1). The reported discharge rates from these wells ranges from less than 1 gpm to 900 gpm, though the highest discharge rates reported probably are not correct. Typical discharge rates are between 10 and 15 gpm.

Springs occur where the water table intersects land surface. As shown on Figure 2, few springs occur at stratigraphic levels below the top of the Lebo Shale. Figure 3 shows typical depths of all water-supply wells in relation to subsurface geology along a geologic cross section from the Montana/Wyoming state line, north to the Yellowstone River. In general, it can be seen that wells tend to follow specific geologic horizons, thus well depths reflect the underlying geologic structure.

The Lebo Shale, which underlies the Tongue River Member, is 75 feet to 200 feet thick and is predominantly shale, with minor shaley sandstone and shaley coal. The Lebo Shale forms an aquitard that separates aquifers (and impacts to aquifers) in the Tongue River Member from those in the underlying Tullock Member. The Lebo is not a target for injection nor would injection into other units have significant effects on the Lebo Shale. The approximate area of the Lebo Shale outcrop, and the structure of the unit are shown on figures 1, 2, and 3.

The Tullock Member is 300 feet to 500 feet thick and consists predominantly of sandstone and shale. Ground-water flow is generally northward toward the Yellowstone River. Recharge occurs in areas of outcrop along the margins of the PRB, and additionally by limited vertical leakage from the overlying geologic units. Discharge occurs along outcrops and where the Tullock subcrops to streams such as the Tongue River. The Tongue River receives about 13 cfs of baseflow from the Tullock Member between the Brandenburg Bridge and Miles City (Woods, 1981; Vuke and others, 2001a; Vuke and others, 2001b). Water quality in the Tullock Member is similar to that found in the deeper portions of the Tongue River Member, and is dominated by ions of Na, HCO_3 and SO_4. Total dissolved solids concentrations range from 400 mg/L to 5,000 mg/L and average about 1,500 mg/L (GWIC).

The Tullock Member is identified as the source of water for 2,905 stock and domestic wells identified in GWIC in the PRB between the Wyoming state line and the Yellowstone River. These wells are located near or north of the Lebo Shale outcrop (figures 1 and 3). Yields from these wells are similar to those reported for the Tongue River Member, ranging from less than 1 gpm to 900 gpm, but again the highest discharge rates are probably not actual pumping rates for Tullock Member wells. Typical discharge rates are between 10 gpm and 15 gpm (GWIC).

Directly beneath the Tullock Member are the Lance/Hell Creek formations and the underlying Fox Hills Formation. The Lance Formation and the Hell Creek Formation are stratigraphically equivalent, but the Lance consists of thick sandstone beds, whereas the Hell Creek consists of thin sandstone and shale layers. In this paper, the two formations are not distinguished because the location of the contact in the subsurface is not well delineated. The Lance Formation is about 600 feet thick and the Fox Hills Formation is typically about 100 feet thick (Lopez, 2005). The Lance/Hell Creek and Fox Hills formations contain sandstones that are productive aquifers in most areas. Ground-water flow is generally north-northeast (Slagle, 1981). Water chemistry in these formations is dominated by ions of Na, HCO_3 and SO_4; TDS concentrations range from 400 mg/L to 5,000 mg/L and average about 1,500 mg/L (GWIC).

The combined Lance/Hell Creek and Fox Hills formations are the aquifers that supply water to 654 wells identified in GWIC. Reported discharge rates from these wells range from less than 1 gpm to 500 gpm, and are typically between 10 gpm and 15 gpm (GWIC). Again, the highest discharge rates are likely not accurate reflections of the production potential of these aquifers. Nearly all Lance/Hell Creek and Fox Hills wells are located north of the area of outcrop of the Lebo Shale (figures 1 and 3).

Several deeper geologic formations in the PRB area in Montana are identified in GWIC as completion zones for supply wells and are potential injection zones. The Madison Group is dominantly limestone and in particular is a possible target. Ground-water flow in the Madison Group is toward the northeast (Feltis, 1980a). Water chemistry is dominated by ions of Ca, Na and SO_4, and TDS concentrations vary between 1,200 mg/L and 3,000 mg/L (Feltis, 1980b; GWIC).

Within the area where injection wells are likely to be drilled, only a few supply wells are completed in aquifers deeper than the Lance/Hell Creek and Fox Hills formations (Figure 1). Few impacts in deeper aquifers, either positive or negative, would be expected.

Potential Impacts of production-water injection

The effects of injecting CBM-production water will vary depending on site-specific conditions such as the volume or rate of injection, quality of injection water, utilization of other management options, the availability of injection horizons at any one site, and the physical properties (hydraulic conductivity and storage coefficient)of the receiving injection horizon. For the purpose of this discussion, the formations described above are divided into 4 aquifer units: 1) shallow Tongue River Member aquifers (these crop out above the local valley floor and are only partially saturated; they are penetrated by the shallow wells at the south end of the cross section shown in figure 3); 2) deeper Tongue River Member aquifers (units below local valley floor but above the Lebo Shale; these are penetrated by most of the wells north of Hanging Woman Creek in the cross section shown in figure 3); 3) the combined Tullock Member, Lance/Hell Creek and Fox Hills formations (penetrated by wells north of the Lebo outcrop in the cross section on figure 3); and 4) the Madison Group.

Shallow Tongue River Member zones

Sandstones and coals that crop out along valley walls near injection wells are not primary injection targets because injected water would likely flow toward the outcrop and form seeps. The quantity of water that could be injected and the injection pressure would be severely limited in order to avoid the formation of seeps. Some locations may, however, be favorable for shallow injection, given the low cost of completing wells in these settings. Edges of the PRB are an example, where geologic units dip away from the outcrop toward the center of the basin and flow within the aquifer is predominately downdip.

Receiving water quantity

The quantity of water that could be injected into unsaturated zones of sandstone and coal would be limited by the porosity of the formation over the area of influence and the rate at which water would flow away from the outcrop under the existing hydrostatic pressure. Only limited areas will be appropriate, such as where the geologic dip is sufficient to create a hydraulic head that drives water down-dip, away from the outcrop; or where unsaturated conditions exist in the outcrop area. Calculations based on a hypothetical setting indicate a 20-foot thick coal bed, with 10% porosity might accept injected water at a rate of 50 gpm for a period of between 1 and 2 years if the above conditions were met and the area of influence for the injection well reached a radius of 1,000 feet. After filling the initial pore volume, additional water could be injected only at the rate at which water flowed away from the outcrop area. Given a range of hydraulic conductivity values for sandstone and coal from 0.015 feet per day (ft/day) to 13 ft/day (Wheaton and Metesh, 2002), the injection rates would likely be less than 10 gpm, but in some extreme cases might reach 50 gpm.

Infiltration ponds are located in similar settings and have been shown to increase water levels in receiving aquifers. The bottoms of ponds, however, tend to seal as the clays disperse in response to the high-sodium content CBM-production water, and have a limited effective life. Infiltration from both ponds and shallow injection wells fill the unsaturated pores prior to the water flowing through the established aquifers.

The effect of injecting water into shallow Tongue River Member aquifers would be to increase flow at down-gradient springs and wells. The timing and duration of such effects are not known. This approach has not been tested, and areas where water could be injected without forming seeps may be very limited.

Receiving water quality

Shallow ground-water chemistry in the PRB is dominated by ions of Ca, Mg, Na, SO_4 and HCO_3 and is controlled by calcite, dolomite and gypsum dissolution, pyrite oxidation, and ion-exchange reactions. Saturation of previously unsaturated aquifer material (whether through the use of injection wells or infiltration ponds) can be expected to initially dissolve additional minerals and increase TDS. A parallel example is the re-saturation of coal-mine spoils during mine reclamation. As the first pore volume of water moves through the spoils a significant but temporary increase in TDS is recorded, followed by flushing of the salts and a subsequent decrease in TDS (Van Voast and Reiten, 1988).

As the injected water joins the original ground water, mixing of different water types would occur. Example calculations showing the results of simple mixing models, using water from representative samples are shown on Table 1. Major-ion concentrations listed in Table 1 are an indication of possible mixing reactions, and are not predictive of actual CBM injection results. The result of mixing CBM-production water with shallow

Tongue River Member water would likely be an increase in the sodium adsorption ratio (SAR) and pH and a decrease in TDS concentration. Dissolution of gypsum may increase and precipitation of calcite and dolomite may occur. Mineral precipitation has the potential of locally decreasing aquifer porosity and permeability. These wells are used for domestic and stock water and the changes in water quality would not be expected to change the usability of the ground water.

Deeper Tongue River Member zones

In areas where aquifers lie above the Lebo Shale but below local topography, sandstone and coal units are saturated. Some additional water could be injected in to these units, which would increase the confined pressure in the aquifers. As noted previously, the areas where significant receiving sandstones and coals are present are limited. Assessment in many of these areas will be challenging, particularly near faults where aquifer testing may not reveal the presence of no-flow boundaries that will limit injection potential.

Receiving water quantity

The geologic units defined by the deeper Tongue River Member zones are confined aquifers. Because these units do not crop out locally, leakage through springs is not a concern. Injection of water will increase the hydrostatic pressures within the formation, resulting in a pressure gradient that spreads through the aquifer. It is important to note that pressure changes will be transmitted within the aquifer much more quickly than injected water can flow through the aquifer. The most immediate effects will be increased water levels (and production) in nearby supply wells, and on a longer term, similar effects at more distant wells and eventually to distant springs. The most likely sandstone targets are channel sands, which have long, narrow shapes. No attempt is made here to calculate ground-water flow and the changes in head that might result from injection into these narrow bodies because the dimensions are not known.

The limiting factor on the amount of water that can be injected into any unit will be the increase in hydrostatic pressures within the formation. If the hydrostatic or water pressure exceeds the confining strength of the formation, the formation will be fractured. This could result in propagation of fractures to other geologic units or possibly to the surface. The controls on the rate of pressure buildup in any individual unit will include the injection rates and physical characteristics of the unit such as thickness, aerial extent, and permeability. Thus, each receiving unit would have to be separately evaluated.

Receiving water quality

The quality of water in Tongue River Member aquifers is site specific. Total dissolved solids concentrations range from 500 mg/L to 5,000 mg/L, but 1,000 mg/L to

2,000 mg/L concentrations are most common (U. S. Bureau of Land Management, 2003, GWIC). Water chemistry in these aquifers is typically dominated by ions of Na and HCO_3, therefore injecting CBM water that has similar chemistry should result in little change in the receiving water quality or usability. However, in areas where the TDS of the formation waters is high, SO_4 concentrations also tend to be high and Ca and Mg may be more prevalent than Na and HCO_3. Injecting CBM water into these zones mixes waters having distinctly different chemistry, and based on simple mixing models would result in water having an intermediate chemical composition reflecting the volumes of the respective waters being mixed. In practice, chemical reactions would be expected, including precipitation of minerals such as calcite and dolomite, and possibly reactions with previously existing minerals. Mineral precipitation would generally fill porosity within the rocks and decrease permeability, thus reducing the rate and volume of water that could be injected.

Tullock-Lance – Fox Hills

In the northern portion of the PRB, from approximately the outcrop of the Lebo Shale to the Yellowstone River, water supplies are typically withdrawn from the Tullock Member, Lance/Hell Creek and Fox Hills aquifers (Figure 1).

Receiving water quantity

These geologic units are confined aquifers but with greater lateral continuity of sandstone units than the Tongue River Member. The amount of change in water levels, gradient and flow will depend on the amount and locations of injected water and the aquifer characteristics. The present gradient in these aquifers is about 0.01 ft/ft toward the north-northeast (Slagle, 1983). Hydraulic conductivity values, based on tests on the eastern edge of the region, are generally between 0.2 and 3.7 ft/day, porosity is estimated to be about 30% and storativity averages about 0.00015 (Miller, 1979). Changes in pressure and gradient (and therefore ground-water flow) would move much faster than the water itself. Based on a transmissivity value of 40 feet squared per day and an injection pressure equal to 500 feet of water, between 60 gpm and 70 gpm of water could theoretically be injected for a period of up to 5 years. At this pumping rate, the head at a distance of 5 miles from an injection well might increase by 5 feet to 10 feet after 2 years and 20 feet after 5 years. Actual injection rates and changes in head will depend on site-specific aquifer characteristics. Injection of CBM-production water into these aquifers will not replenish aquifers impacted by CBM development due to the confining nature of the Lebo Shale (all CBM-producing coals lie above the Lebo), however the water will remain in PRB aquifers and eventually be available to some wells.

Receiving water quality

Based on data in GWIC and those reported by Miller (1979), water chemistry in these aquifers is dominated by Na and HCO_3 and generally has very low concentrations of SO_4 except for a few locations. Based on a simple mixing model, mixing the background water with CBM-production water should produce few chemical reactions other than direct mixing, which would increase the TDS concentration by a small amount (Table 1). Changes in the usability of the water would not be expected.

Madison Limestone

The Madison Group is a thick limestone unit that has been discussed as both a deep source of water and a deep disposal unit for CBM-production water. Although some zones are highly permeable, the Madison Group is not utilized as an aquifer within the PRB because of its depth, approximately 7,000 feet below the Tongue River and as deep as 15,000 feet in the deepest part of the PRB (Konikow, 1976).

Receiving water quantity

The potentiometric surface of the Madison Group indicates a gradient of approximately 0.01 ft/ft to the northeast (Feltis, 1980a). Konikow (1976) reported that between 100 cfs and 400 cfs of ground water flows through northeast Wyoming, southeast Montana and western South Dakota. Roughly one-quarter of that water likely flows through the PRB in Montana. Injection of CBM-production water would raise the potentiometric surface, increasing the gradient and the rate of flow to the northeast. Injection of water into the Madison Group would not conserve the ground-water resource, and, as such, it may be a better target for disposal of water such as brines from treatment plants than for general production water in Montana. High yield to wells, or injection capacity in the Madison Group depends on intersecting fractures and solution voids that provide porosity and permeability. Fracture density and connectivity in the Madison Group varies considerably and wells completed in this unit have a wide range of yields.

Receiving water quality

Water in the Madison Group in southeastern Montana has a TDS concentration ranging from 1,200 mg/L to 3,000 mg/L and is dominated by ions of Ca, Na and SO_4 (Feltis, 1980b; GWIC). The temperature of ground water in the Madison Group in this area is reported to reach 100 °C (Konikow, 1976; Sonderegger and other, 1981). Injection of CBM-production water would increase HCO_3 concentrations, decrease TDS and SO_4, and lower the temperature depending on the volume and rate of injected water. The increased HCO_3 concentration would allow precipitation of calcite. The temperature would equilibrate with the geothermal gradient. The usability of the water would not change in response to injection operations.

Conclusions and challenges

Management of production water is a major concern for CBM producers and landowners alike. Injection is one choice the CBM operators consider for management of produced water.

The Montana Environmental Impact Statement (U. S. Bureau of Land Management, 2003, page 4-61) estimated a maximum water production rate of 3.4 billion cubic feet (80,000 acre feet) per year, or about 48,000 gpm. Injection of this quantity of water into aquifers that might receive 10 gpm to 70 gpm as discussed above (discounting Madison Group disposal wells), would require 700 to 5,000 injection wells.

In general, injection of produced water will increase pressures in the receiving aquifers, increasing the flow of water and the quantity of water available from wells and springs in the immediate area. In areas where injection into the shallow Tongue River Member units is undertaken, careful planning and monitoring will be needed to avoid surface seepage of the injected water.

Mixing injected water with receiving water that contains Ca and Mg will, in most cases, cause precipitation of calcite and dolomite. The precipitation of minerals will decrease pore size and hydraulic conductivity in the vicinity of the injection well, possibly decreasing the potential rate of injection. Mixing models of the injection did not indicate any situations where the usability of the water in the receiving aquifer would change.

Overall, the approach of injecting water into Fort Union Formation aquifers has not been widely tested. Areas where favorable conditions exist appear to be limited to a small percentage of the total area. Mandating injection does not mean it is technically feasible, regardless of economics. In some areas that have suitable aquifers, injection may be technically and economically feasible, as well as a means of conserving the water resource. However, injection cannot be regarded as appropriate in all settings, and further, mandated injection may force the use of the Madison Group and actually decrease water that is retained or utilized within the Powder River Basin.

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Table 1. Results of mixing models of background water quality from monitoring wells in the Powder River Basin. The results are intended to demonstrate ranges of possible values and are not intended to demonstrate predictive capabilities. All units are in mg/L, except pH.

Aquifer	Site name	Baseline							Mixed 90% CBM-produced water 10% baseline water							Mixed 50% CBM-produced water 50% baseline water						
		TDS	Ph	Ca	Mg	Na	HCO3	SO4	TDS	pH	Ca	Mg	Na	HCO3	SO4	TDS	pH	Ca	Mg	Na	HCO3	SO4
CBM	SL-5CC	1242	8.2	5.1	3.3	556	1288	0														
Shallow Tongue River																						
Coal	WRE-11	1611	8.6	8.7	4.2	670	1596	0														
	BS-07	1866	8.4	234	219	90	628	972	1280	8.2	28	25	510	1250	97	1510	8.2	116	111	324	970	487
	BS-30	3961	7.2	482	456	133	969	2365														
Sandstone	BS-02	2185	7.4	152	277	135	635	1269	1310	8.0	20	31	515	1260	127	1670	7.7	79	141	346	960	636
Deep Tongue River																						
Coal	CBM-8FG	1321	9.0	2	0.6	520	767	297	1210	8.3	5	3	553	1260	30	1200	8.6	4	2	539	1020	149
Sandstone	CBM-8DS	1053	8.6	6.3	3.1	412	1104	10.5	1190	8.2	5	3	543	1300	1	1090	8.4	6	3	484	1200	5
Tullock, Lance, Hell Creek and Fox Hills formations																						
Tullock	IP-02	996	8.3	2	0.9	412	1101	0	1190	8.2	5	3	543	1300	0	1090	8.3	4	2	485	1210	0
	IP-05	1288	8.5	2.2	1	467	708	434														
Fox Hills	B 108 2	560	8.5	2.6	0	220	450	10														
Hell Ck	B 108 3	780	8.4	4.2	0	320	410	280	1170	8.2	5	3	533	1230	28	1010	8.3	5	2	439	870	140
Madison Group																						
	M:895182	2383	7.9	300	44	460	770	1100														
	M:895465	1367	6.9	220	35	170	148	770	1220	8.1	27	7	518	1210	77	1250	7.8	113	19	364	750	385

Sources of data: GWIC; Miller, 1979
Mixing model: PHREEQC

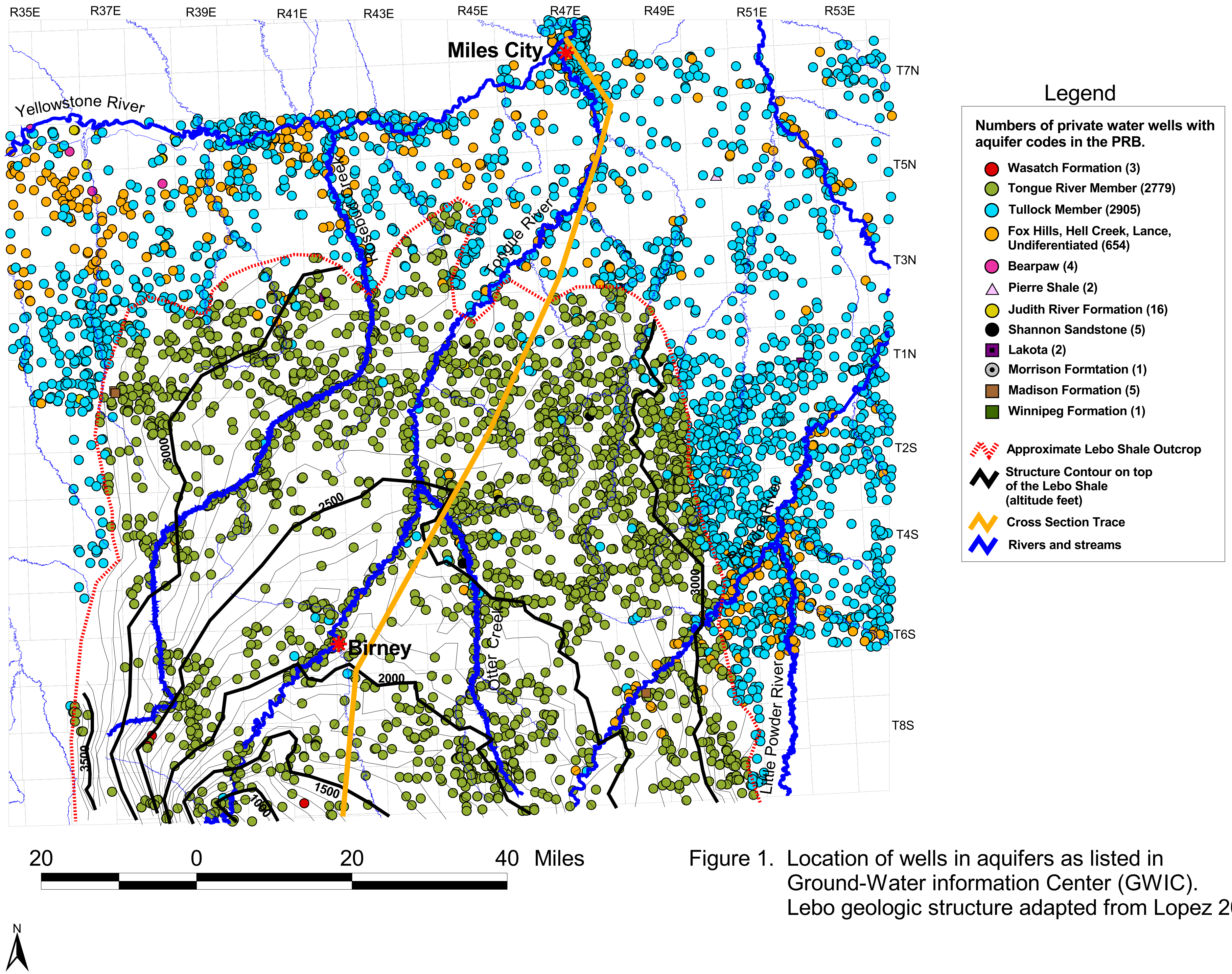

Figure 1. Location of wells in aquifers as listed in Ground-Water information Center (GWIC). Lebo geologic structure adapted from Lopez 2005.

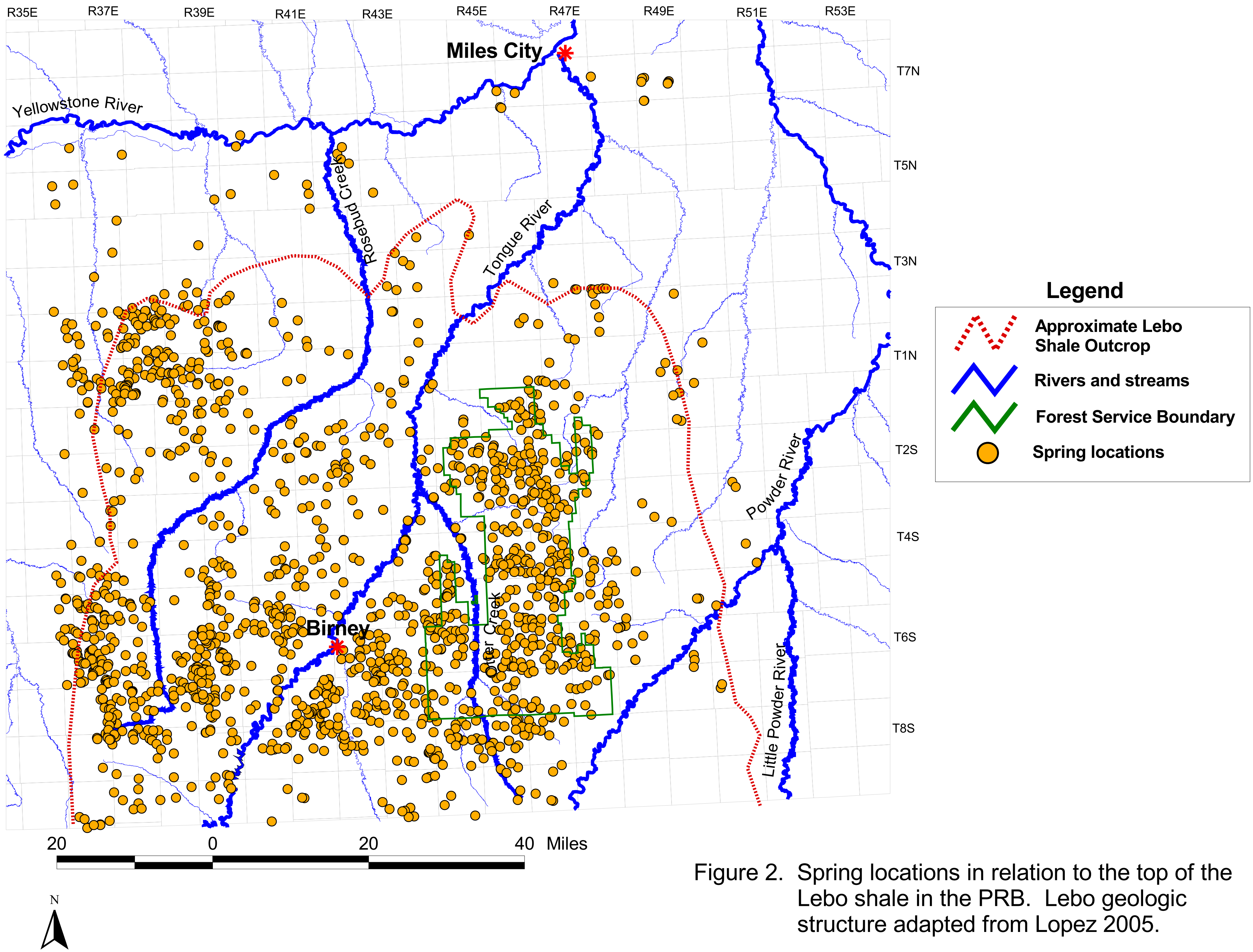

Figure 2. Spring locations in relation to the top of the Lebo shale in the PRB. Lebo geologic structure adapted from Lopez 2005.

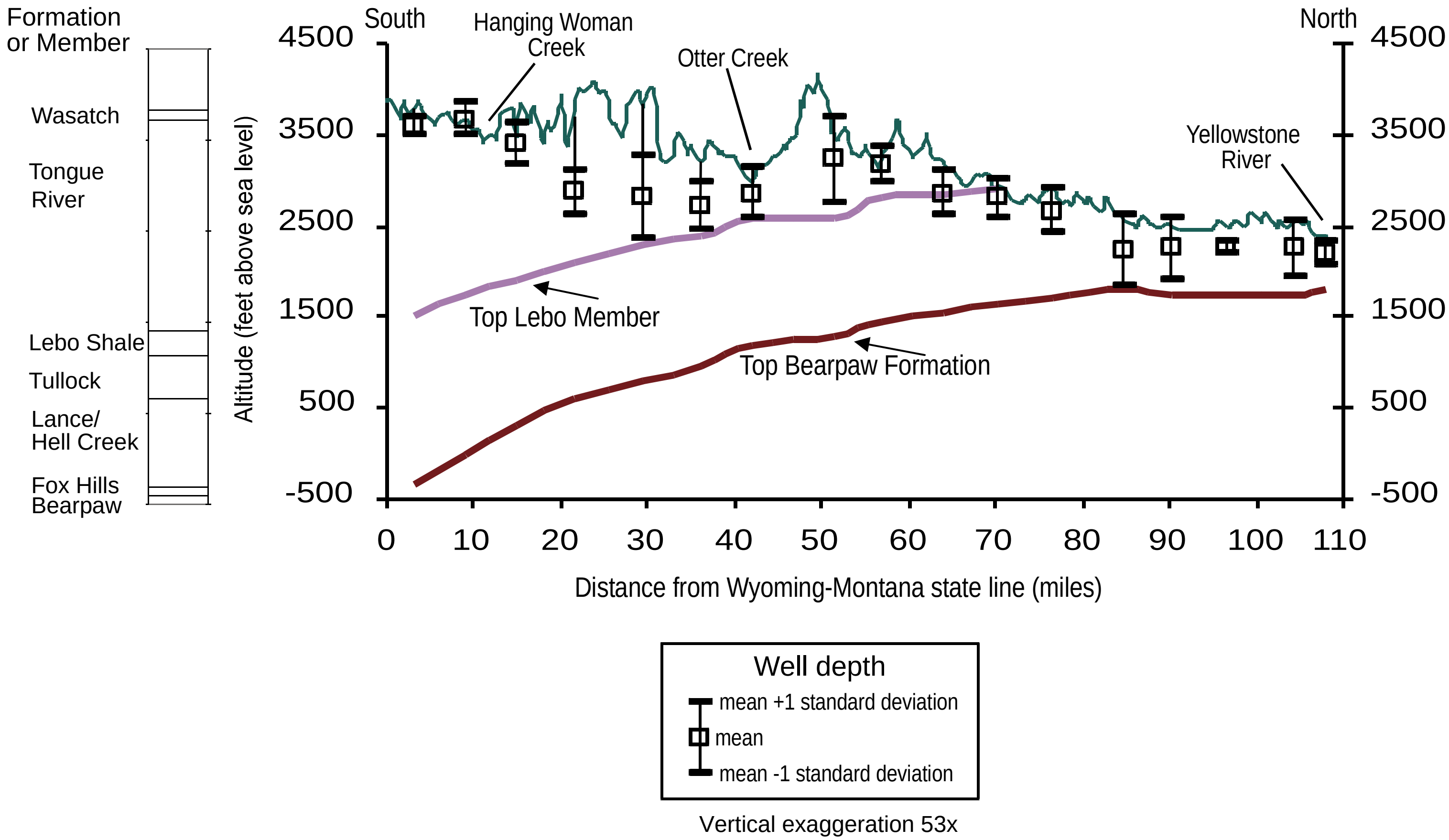

Figure 3. Well depths projected from one Range east and west of cross section trace.
Location of cross section trace is shown in Figure 1.
Lebo and Bearpaw geologic structure adapted from Lopez 2005.